DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/13

Log-derived acoustic impedance versus porosity and porosity versus depth trends in the Chalk Group

Examples from the southern Danish Central Graben

Lars Kristensen & Claus Andersen

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Contents

Introduction and Background

Seismic inversion techniques are routinely used to predict and map porosity distribution in the Chalk Group. Knowledge of acoustic impedance (AI) derived from seismic data is particularly appealing due to a robust and usually well-defined correlation between acoustic impedance and porosity caused by the generally mono-mineralic nature of chalk (calcite) with only minor amounts of shale and silica impurities.

Mærsk has established a relationship between apparent (or total) porosity and log AI based on a large number of wells located in the Danish Central Graben (described in e.g. Jacobsen *et al* 1999). The conversion to porosity from AI was performed using a second order polynomial regression. The apparent or total porosities (*PHIT)* omitting gas-bearing intervals were calculated using solely the density log. Using the density alone in the porosity estimation introduces an error in the porosity estimate compared to the effective porosity *(PHIE)*, since no correction is made for hydrocarbon and shale content. Use of PHIT instead of PHIE for correlation with seismically derived porosity estimate is considered the most applicable, since the porosity derived from the seismic is 'bulk' porosity including any porosity bound in clay (e.g. clay bound water) and other minerals.
Mærsk analysed the distribution of errors in well log AI-derived PHIT relative to well log PHIT (corresponding to the scatter around the regression line). The standard deviation of the distribution is 2.4 porosity units indicating that PHIT in most water-bearing chalks can be estimated quite accurately from AI-data.
Similar high correlation between porosity, and seismic velocities and densities are reported from chalks in the Norwegian Ekofisk province (Anderson, 1999).

A similar approach to investigate the relationship between log AI and porosity (PHIE) has been employed by Vejbæk (2002) for porosity mapping in the Dan and Kraka area. However, the database was rather restricted comprising only three Dan Field wells and one Kraka Field well, none of them penetrating the full chalk section. This gives a narrow control range of data points. To achieve a realistic extrapolation beyond data control points, acoustic impedance at 0% (matrix properties) and 100% porosity (fluid properties) was added to the data base and an exponential function was fitted to describe the log AI- PHIE relationship.
Klinkby et al. (2005) applied a different approach to map the porosity distribution in the Danian-Maastrichtian reservoir intervals of the Kraka Field. They established a linear correlation between average AI values extracted directly from the seismic impedance cube and the average log porosities for the intervals in selected Kraka and Dan Field wells.

The objective of the present study is to analyse and illustrate the effect of shale and gas in the chalk on the log AI versus PHIT relationship making use of available log porosity interpretations by GEUS from wells located in the southern Danish Central Graben area. Further, the log AI – PHIT relationships are analysed for each litho-stratigraphic subdivision of the Chalk Group. The porosity-depth trends in the chalk have been analysed both as composite plots for full well sections and split into units and compared with the classical model by Scholle (1977). The porosities have been plotted both versus TVDSS and effective depth, the latter to compensate for the effects caused by overpressure.

Database

Log data from 14, predominantly vertical exploration wells have been analysed of which eight penetrate the entire chalk section. This selection secures a wide range of porosity values (from close to 0 to more than 40%) The wells are listed below:

Dan:	M-8x*, M-9x, M-10x
Kraka:	Anne-3*, A-4P, A-10P
Halfdan:	Nana-1xp*, HDN-1x
Halfdan NE:	Sif-1x, G-1x*
Gorm:	N-22*
Outside fields:	Skjold Flank-1*, U-1x*, Sine-1xp*

A well marked with * indicates that the entire chalk section has been penetrated. Note that Sine-1xp is located on the footwall block of the Coffee Soil Fault.

Methods

As stated above total porosity (PHIT) has been calculated from the density log readings (RHOB). The following equation has been used:

$$\text{PHIT (fraction)} = \frac{2.71 - RHOB}{2.71 - 1.05} \qquad (1)$$

The density of calcite is 2.71 g/cm^3 and fluid density is assumed to be 1.05 g/cm^3.

The effective porosity (PHIE) is calculated from a shale corrected density log. The calculation of the shale volume is described below.

The shale volume (Vshale) as fraction is calculated from the gamma ray response as

$$\text{Vshale} = \frac{GR - GRclean}{GRshale - GRclean} \qquad (2)$$

GRclean is the minimum GR response in the chalk section and GRshale is the maximum GR-value in the overlying Paleocene shales. The latter value is typically in the range of 100-120 API-units.

The gas zones have been defined directly from the separation observed on the neutron-density logs.

The acoustic impedance (in m/sec*g/cc) is calculated from the density and sonic logs.

The effective depth (Z_{eff}) is related to the overpressure (ΔP) as described by Japsen *et al* (2005):

$$Z_{eff}(m) = Z(m) - 100 \cdot \Delta P(MPa) \qquad (3)$$

where Z is the true vertical depth subsea (in metres). This equation is used for calculating 'overpressure-corrected' depths.

Results

The results of the study are presented in the following text and in the attached figures.

Acoustic impedance versus porosity – clean chalk

A composite plot of log AI vs. PHIT for the 14 wells, with a Vshale cut-off of 2% applied excluding gas zones, is shown in Fig.1. In this type of clean chalk PHIT is close to PHIE. A well-defined correlation exists with only minor scatter around the second order polynomial regression line as illustrated on the frequency plot (Fig.2).
The conversion from log AI to PHIT can be expressed as:

$$\text{PHIT (fraction)} = 0.729 - 7.08*10^{-5}\text{AI} + 1.55*10^{-9}\text{AI}^2 \qquad (4)$$

The regression line with a Spearman rank-order correlation coefficient of $r^2 = 0.96$ has been forced to fit the 0 % porosity point at an AI-value of 15674 m/sec*g/cc equivalent to a mineral density of 2.70 g/cc and V_p at 5810 m/sec. This equation leads to a conversion from AI to PHIT that is almost identical to the one established by Mærsk in 1998 with less than 1% difference in porosity for similar AI-value.

Velocity (V_p) versus porosity – clean chalk

In Fig.3, PHIT for the clean chalk without gas is plotted vs. V_p. The spread of data-points is within the empirically modified upper and lower Hashin-Shtrikman models (Walls et al. 1998) and reflect differences in pore stiffness.

Acoustic impedance versus porosity – shale-rich beds included

Plots of log AI vs. PHIT and the corresponding frequency plots for the wells without Vshale cut-off and gas are shown in Figs 4 & 5. As expected the spread of data is larger compared to the clean chalk Fig.1 with the r^2-value slightly reduced to 0.94.

Shale and gas effects

In order to isolate the effect of shale, AI vs. PHIT is plotted for chalk without gas but with shale volume larger than 10% in Fig.6. Most data points are clearly located below the regression line defined for the clean chalk and use of equation (4) for conversion from AI to PHIT will locally overestimate total porosity up to 5 p.u. In lower Ekofisk and in the deeper parts of the chalk section, where increased shale contents may occur, the potential effect should be borne in mind when interpreting acoustic impedance results.

The gas effect is shown in Fig.7 in which AI vs. PHIT for gas-bearing chalk is plotted using a 5% Vshale cut-off. According to the theory, presence of gas results in lowering the acoustic impedance. This effect is clearly illustrated as data points tend to be located below the regression line defined for clean chalk without gas. Comparing Fig.6 with Fig.7 this overestimation of porosity tends to be slightly less for gas zones than in shale-rich intervals.

AI vs. PHIT plots for three selected wells

Figs 8-10 show the AI vs. PHIT plots for three selected wells (N-22, Nana-1xp and Skjold Flank-1), all penetrating the entire chalk section and representing a porosity range of more than 30 p.u. No Vshale cut-off is applied. The well sections have been split into 6 units with the Tor Formation divided into an informal upper and less porous lower part separated by an arbitrarily selected, but clearly mappable seismic marker tying the wells. Similarly, the Hod and Hidra Formations have been split into an informal Upper Hod unit and 'Lower Chalk' separated by a distinct intra-Hod unconformity that can clearly be identified on seismic data.

The data points for N-22 plot more or less on top of the regression line defined by equation 4 indicating a clean, almost shale-free chalk. In Nana-1xp shale effects are clearly recognized in lower Ekofisk and in the 'Lower Chalk' unit, whereas shale effects in Skjold Flank-1 are mostly restricted to the Ekofisk Formation.

Comparison: N and S part of the Central Graben area

The AI vs. PHIT relationship for the 14 wells from the southern part of the Danish Central Graben are compared with that of three selected wells located in the northern and north-western part where log porosity interpretations are available. The data points for Gert-1, Jeppe-1 and Tordenskjold-1 all plot close to the regression line for clean chalk defined in the south when a Vshale of 2% cut-off is applied (Fig. 11). This is in contrast to the spread of data points seen in Fig.12 where no Vshale cut-off has been applied. The effect of higher shale content - especially in the deeper, tighter parts of the well sections - is distinct.

In order to compare the porosity – velocity relationships of chalk between the southern and northern Danish Central Graben, PHIT vs. V_p data from Karl-1, located just south of the Norwegian border-line, have been plotted both with and without V-shale cut-offs (Figs 13 & 14). Focus on the Karl-1 well is relevant as it is used as calibration well for estimating chalk porosity directly from sonic data in the widely used GR-DT lithology method. The original choice of Karl-1 for calibration purposes is attractive as it penetrates a thick chalk section and exhibits a wide porosity range. The second order polynomial regression line shown on Figs 13 & 14) is identical to the one displayed on the composite PHIT vs. V_p plot of the 14 southern wells on Fig. 3. In the clean chalk case (2% Vshale cut-off) the Karl-1 data plot very closely around the regression line indicating that the PHIT vs. V_p relationship established in this well also is suited to estimate porosity directly from sonic data in clean chalk in the south. Without applying Vshale cut-offs a scatter of data point below the regression line is observed reflecting shale-rich intervals in the well section.

Porosity – Depth trends

The porosity-depth trends in the chalk from the 14 wells have been analysed, both as composite plots for full well sections and split into units and finally compared with the classical model by Scholle (1977). This model predicts porosity as a function of burial depth and is based on empirical data of normally compacted chalk without overpressure and hydrocarbons. The effective porosities (PHIE) as interpreted from the logs data have been plotted both versus true vertical depth (TVDSS) and versus effective depth (Z_{eff}).

Chalk Group

The composite PHIE vs. TVDSS plot (Fig.15) reveals that the trends deviate considerably from the Scholle curve within the Chalk Group: More than 20% excess porosity is observed in the shallow part of the chalk sections, but the basal part is characterised by rapid porosity deterioration with depth approaching the Scholle model.

Overpressuring is widely accepted as a major factor in controlling porosity preservation in North Sea chalks (e.g. Japsen, 1994, 1998). Overpressures develop where rates of overburden sediment loading are high and fluid escape rates are low. In order to correct for the effect of overpressure in the chalk (6–10 MPa in the study area) PHIE for all 14 wells have been plotted vs. effective depth (Z_{eff}), which corresponds to the depth where the effective stress (S_{eff}) would occur during normal compaction. The trend for the shallow parts of the chalk section now resemble that of the Scholle curve (Fig.16) whereas the data points representing an effective depth greater than app. 1750m all plot to the left of the model. The marked drop in PHIE and loss of effectiveness of overpressure to maintain high porosities at this effective depth has also been recognized by Japsen et al. (2005). This phenomenon may be an example of the 'Biot effect'. When sediment grains are held together by cement, pore structure stiffens under elastic deformation, so that the effective stress increases and becomes $S_{eff} = S_0 - \beta P_p$ where S_0 is confining stress, P_p is pore pressure and β (the Biot's coefficient) is less than 1 (Fabricius et al. 2008).

Tor Formation

The PHIE vs. TVDSS and Z_{eff} relationships for the upper part of the Tor Formation are shown in Figs 17 &18, respectively. Two features are noticeable on the plots, firstly the steep porosity gradients (ΔPor/ΔZ) with more than 10 p.u. per 100 m, and secondly the high porosities recorded in the uppermost parts of the unit in wells with hydrocarbons compared to the dry wells. Especially the porosities above 40% in the highly oil-saturated uppermost Tor Formation in N-22 are outstanding. This observation clearly illustrates that oil and gas saturations influence preservation of chalk porosity by impeding chemical compaction significantly.
The porosities in the lower part of the Tor Formation are in most wells reduced to < 25% and the porosity gradient (ΔPor/ΔZ) is lower compared to above (Fig. 19). The data points tend to cluster around the Scholle curve on the PHIE vs. Z_{eff} plot (Fig. 20).

Pre-Tor Formation

The PHIE vs. TVDSS and Z_{eff} relationships for the pre-Tor Formation chalks are illustrated in Figs 21 & 22. A porosity loss to less than 20% in this interval is noticed apart from thin intervals in the shallow Anne-3 well. Thus, the recorded velocity range in the wells suggests that The Hod and Hidra Formations have less than attractive reservoir characteristics at best. As stated above, the porosity trend approaches the Scholle model (Fig. 21). The rapid loss of effectiveness of overpressure to maintain porosity at a Z_{eff} of about 1750m is most pronounced in the Sine-1x well, where it coincides with a distinct unconformity. In Anne-3 and Skjold Flank-1 the gradient appears less pronounced.

Summary and Conclusions

A robust relationship between log-derived acoustic impedance (AI) and total porosity (PHIT) is demonstrated for clean chalk (< 2% Vshale) in the southern part of the Danish Central Graben based on existing log-porosity evaluations of 14 wells of which eight penetrate the entire Chalk Group. A well-defined correlation exists with only minor scatter around a second order polynomial regression line expressed as: PHIT (fraction) = 0.729 – 7.08*AI + 1.55*AI^2. This relationship for clean chalk has been tested and confirmed by using supplementary log-data from three wells located in the northern part of the Danish Central Graben. In order to isolate the effect of shale content, AI vs. PHIT is plotted for chalk with a shale volume > 10%. Use of the above equation will locally overestimate total porosity up to 5 p.u. A similar overestimation of porosity is demonstrated in gas-bearing zones.

The porosity – velocity relationships for clean chalk in the 14 southern wells have been compared with that of the Karl-1 well, which have been used as calibration well for estimating porosity directly from sonic log data in the widely used GR-DT lithology method. The Karl-1 data plot very closely around the regression line established for the 14 southern wells indicating that the Karl-1 PHIT vs. Vp relationship also is well-suited for porosity estimation in this area.

The porosity-depth trends have been analysed both as composite plots for full well sections and split into units and compared with the classical Scholle Model, which predicts the porosity as a function of burial depth for normally compacted chalks. The recorded trends deviate considerably from the Scholle curve with more than 20% excess porosity in the shallow parts and rapid porosity deterioration with depth approaching the model in the basal part of the chalk sections. The excess porosities in the uppermost parts are mostly caused by the porosity preserving effects related to the overpressure reducing the effective stress (S_{eff}). However, porosities above 40% are recorded in wells with high hydrocarbon saturations illustrating that oil and gas also influence porosity preservation by impeding chemical compaction significantly. A marked drop in porosity is recognized below an effective depth (Z_{eff}) of about 1750 m. At this level the effectiveness of overpressure to preserve high porosities is lost. Hence in the southern part of the Danish Central Graben, the pre-Tor Formation chalks are generally tight (<20% PHIE) and without reservoir properties unless heavily fractured.

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Figures

Acoustic impedance versus porosity (clean chalk)

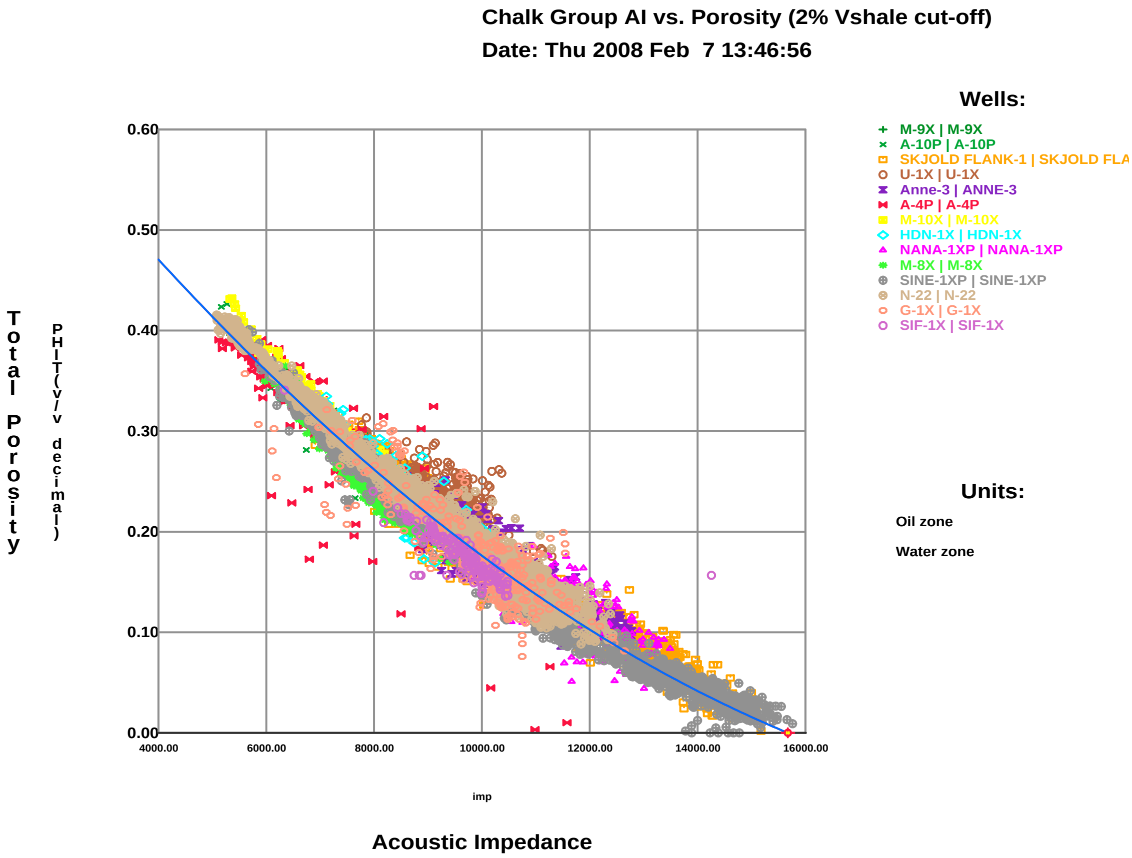

Fig. 1: Acoustic Impedance vs. Porosity for the Chalk Group in the southern part of the Danish Central Graben. Selected wells, 2% Vshale cut-off, gas zones excluded.
AI-PHIT relationship: Porosity = 0.728997-0.00007076249*AI+0.00000000155*AI^2
Spearman rank-order correlation coefficient: 0.96

Frequency plot (clean chalk)

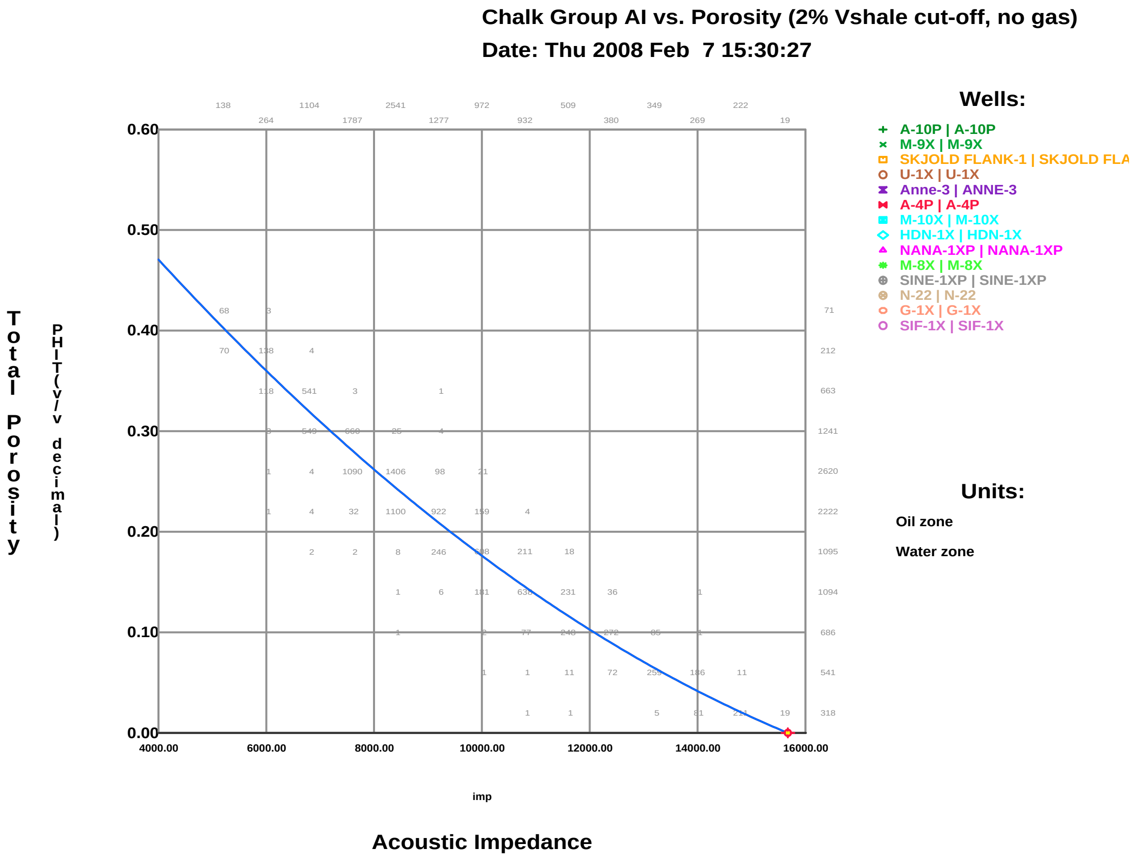

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Fig. 2: Frequency plot for the AI–PHIT data plotted in Figure 1.

Velocity (Vp) versus porosity – clean chalk

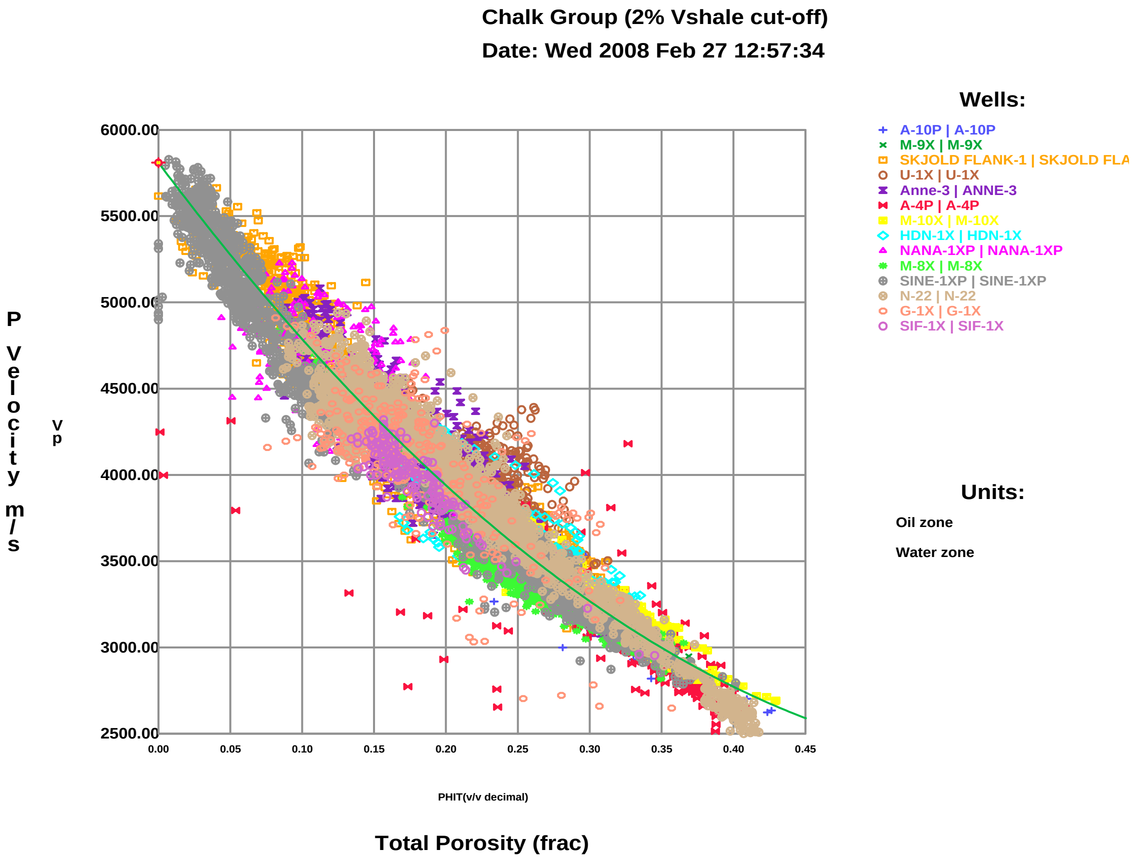


Fig. 3: Chalk Group velocity (Vp) versus porosity for clean chalk (2% Vshale cut-off). Selected wells in the southern part of the Danish Central Graben. One impedance value represent a range of porosities – however, the spread of the data points is within the range defined by the upper and lower Hashin-Shtrikman model equations.

Green line (regression line): $Vp = 5810 – 1110.7*PHIT + 8788.8*PHIT^2$

Acoustic impedance versus porosity (no cut-off)

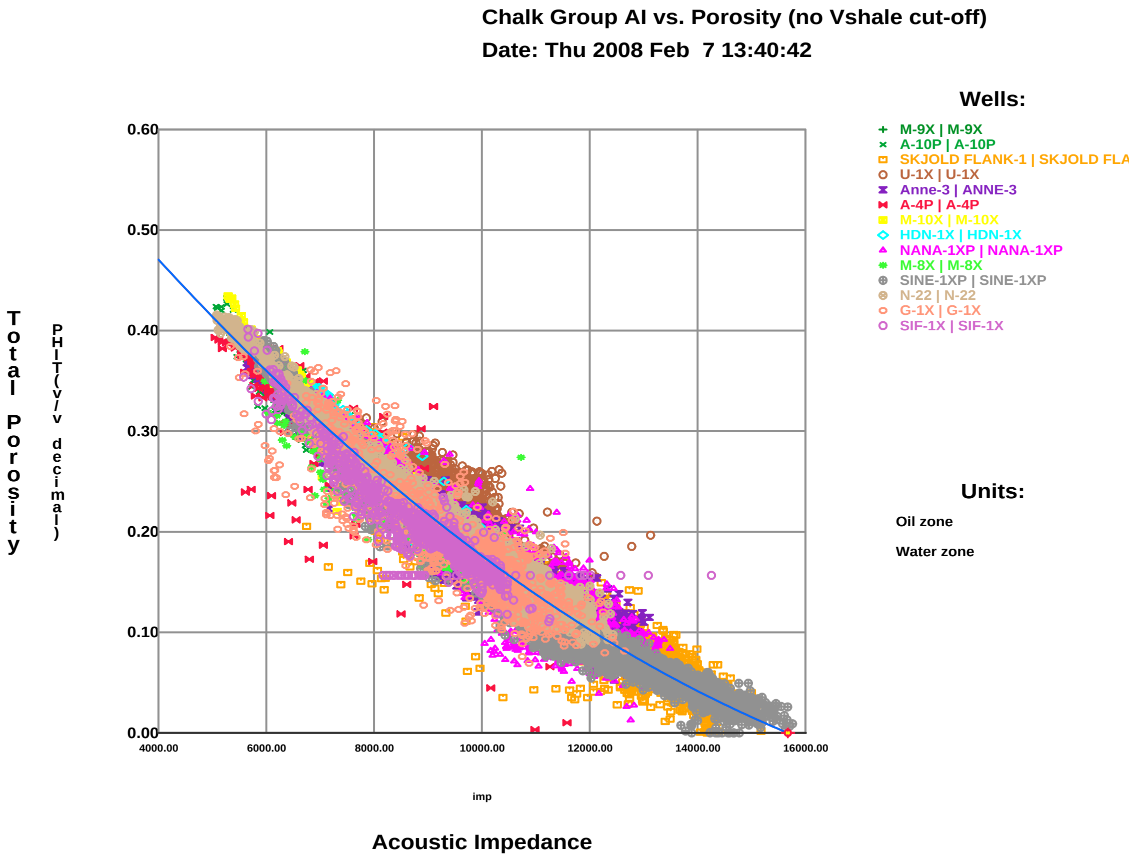


Fig. 4: Acoustic Impedance vs. Porosity for the Chalk Group in the southern part of the Danish Central Graben. Selected wells, no Vshale cut-off, gas zones excluded.
Regression line plotted
Spearman rank-order correlation coefficient: 0.94

Frequency plot (all data)

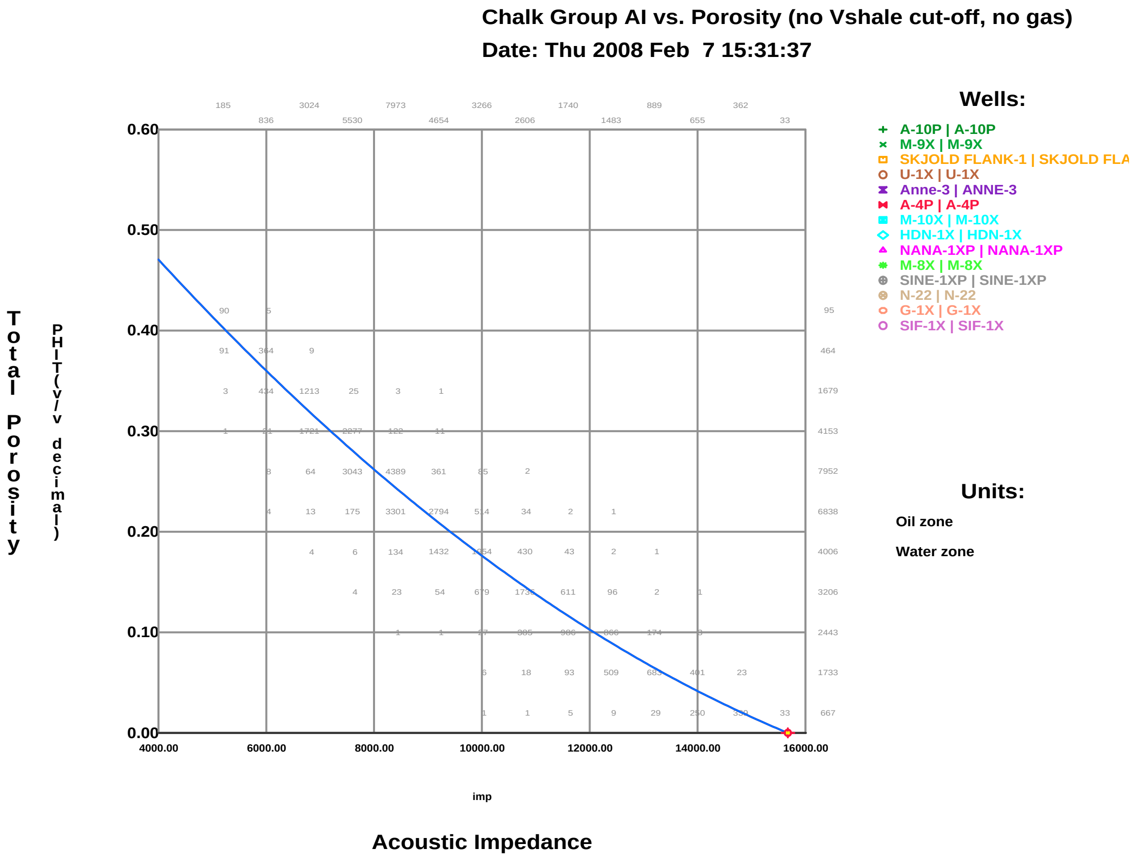


Fig. 5: Frequency plot for the data plotted in Figure 4.

Shale effect on AI

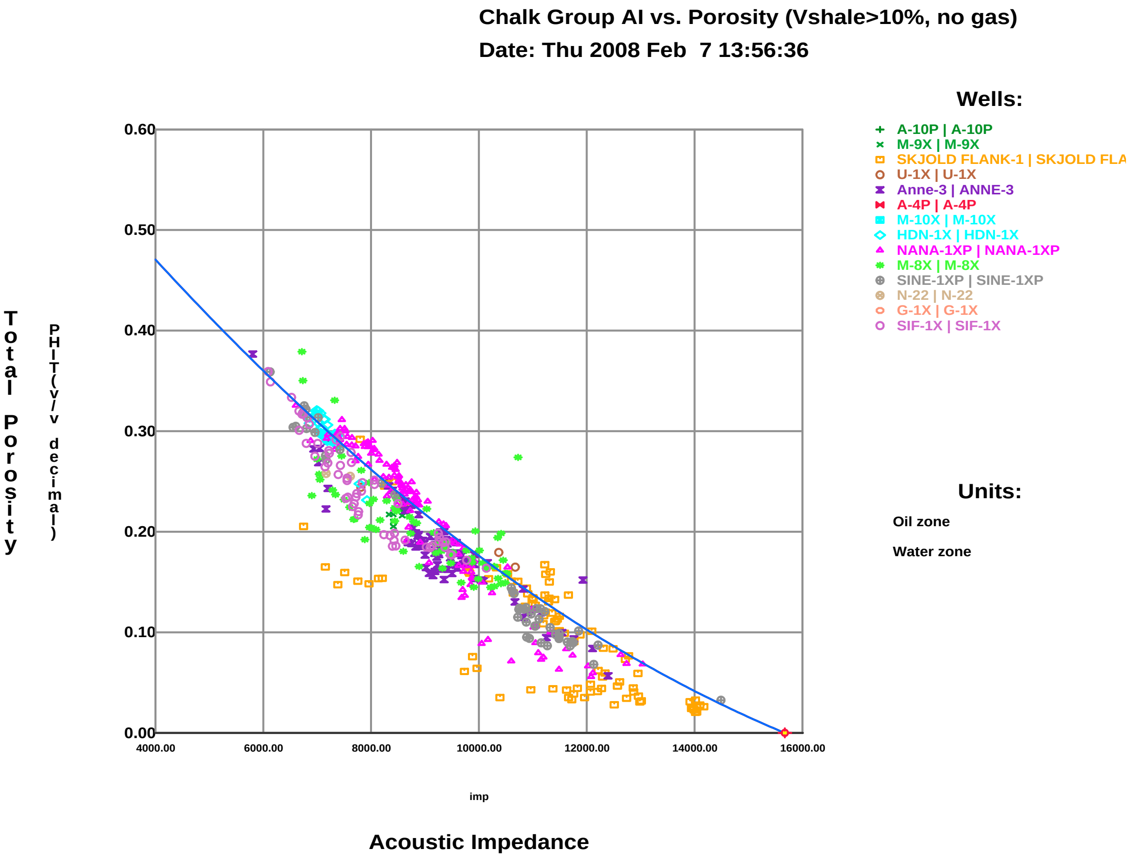


Fig. 6: Illustration of shale effect: only intervals having shale content > 10% are considered. Chalk group acoustic impedance versus porosity. Gas zoned excluded. Regression line as in Figure 1

Gas effect on AI

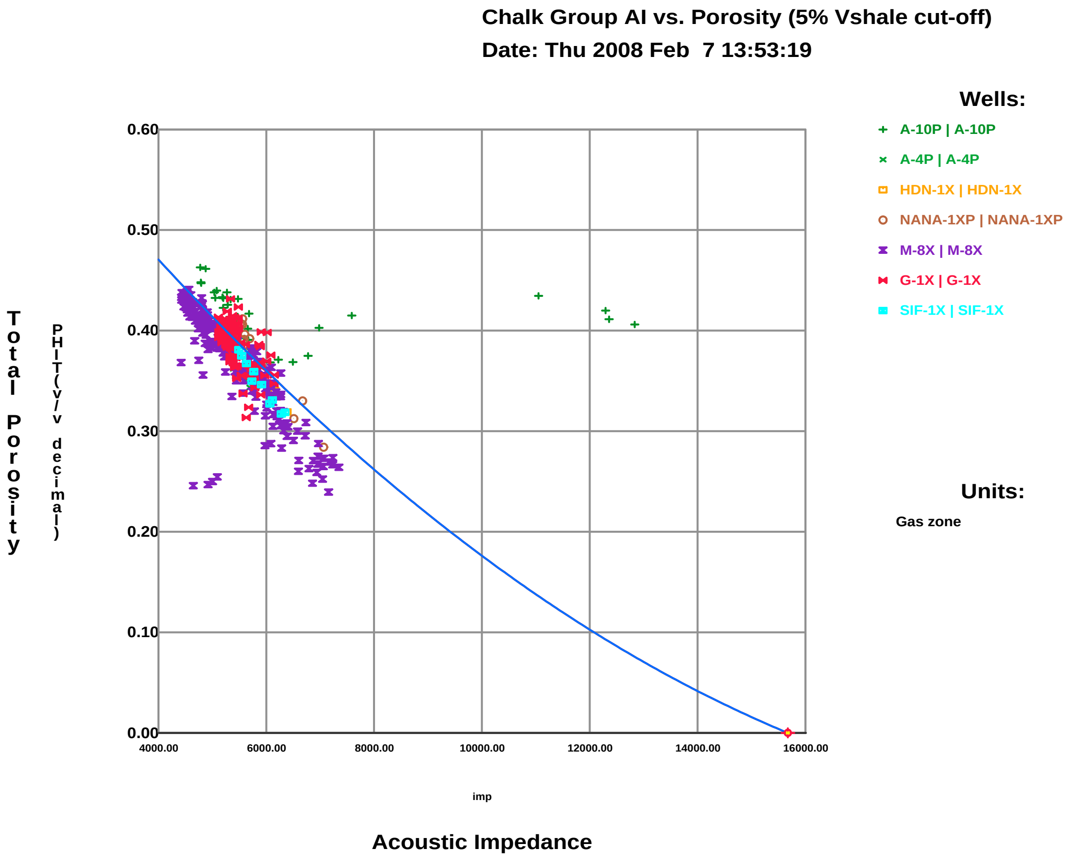


Fig. 7: illustration of gas effect. Chalk group acoustic impedance versus porosity (5% Vshale cut-off applied). Regression line as in Figure 1

AI-PHIT for N-22

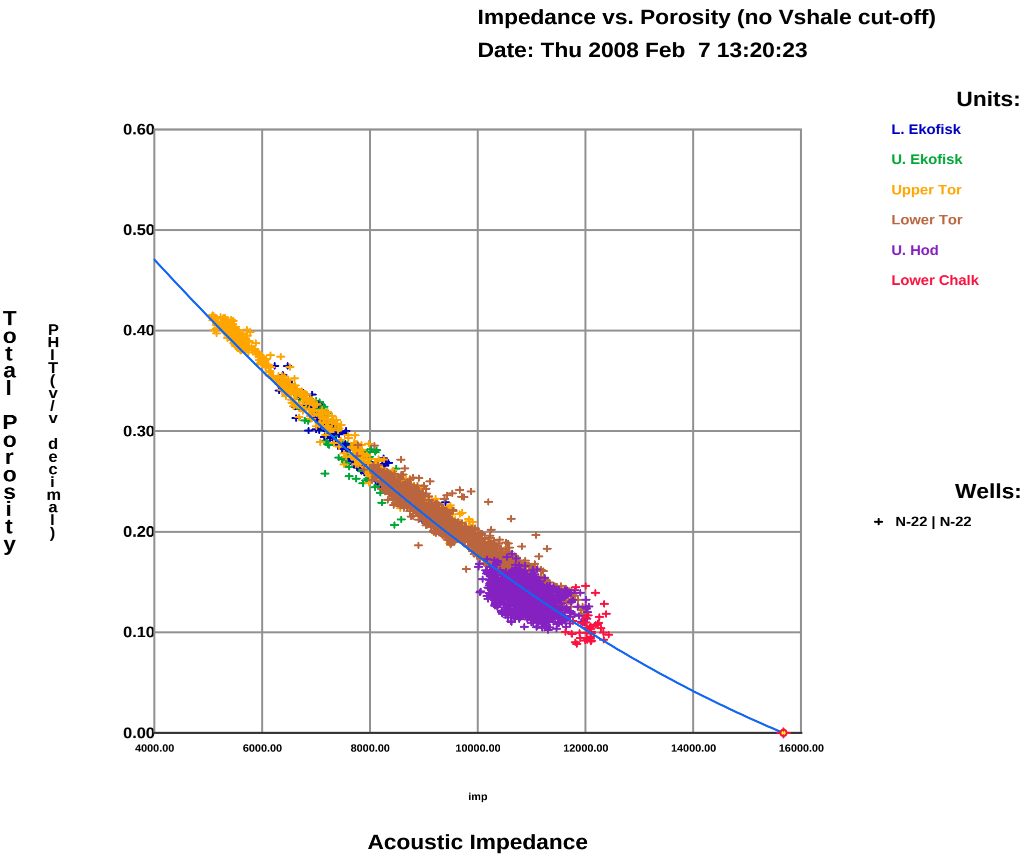


Fig. 8: Well N-22 deep Gorm, AI versus porosity, split into lithostratigraphic units

AI-PHIT for Nana-1

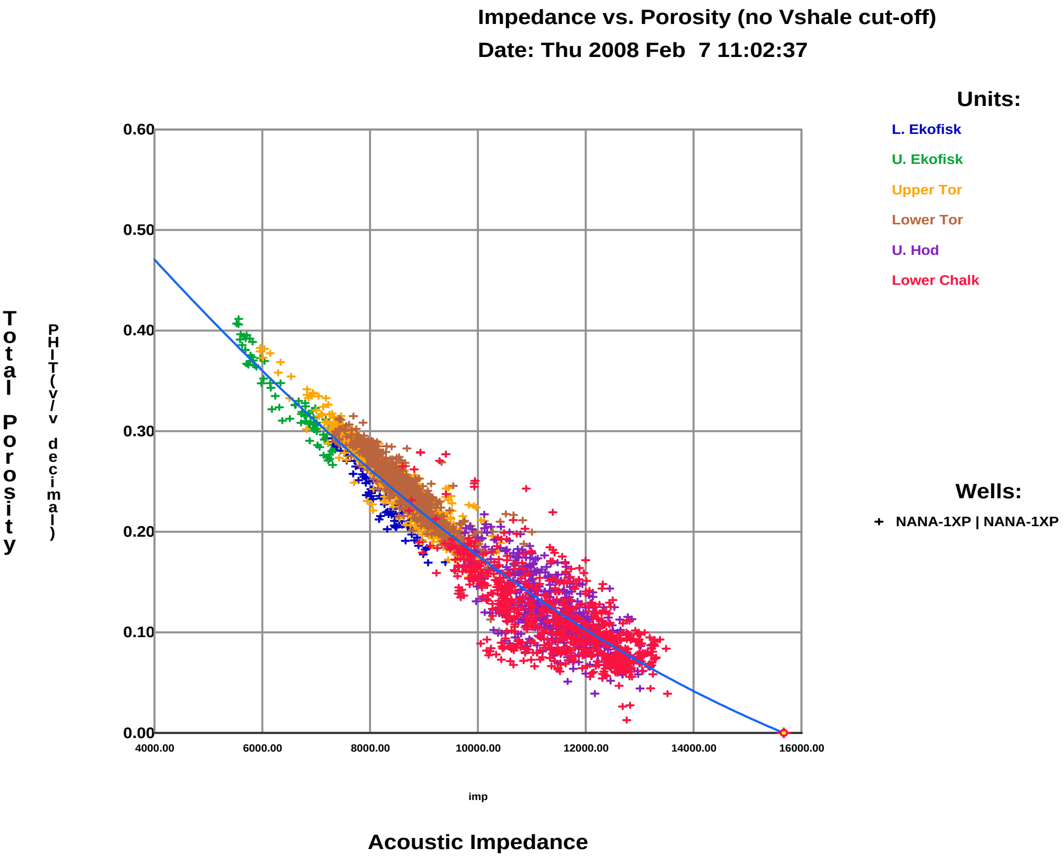


Fig. 9: Well Nana-1, AI versus porosity, split into lithostratigraphic units

AI-PHIT for Skjold Flank-1

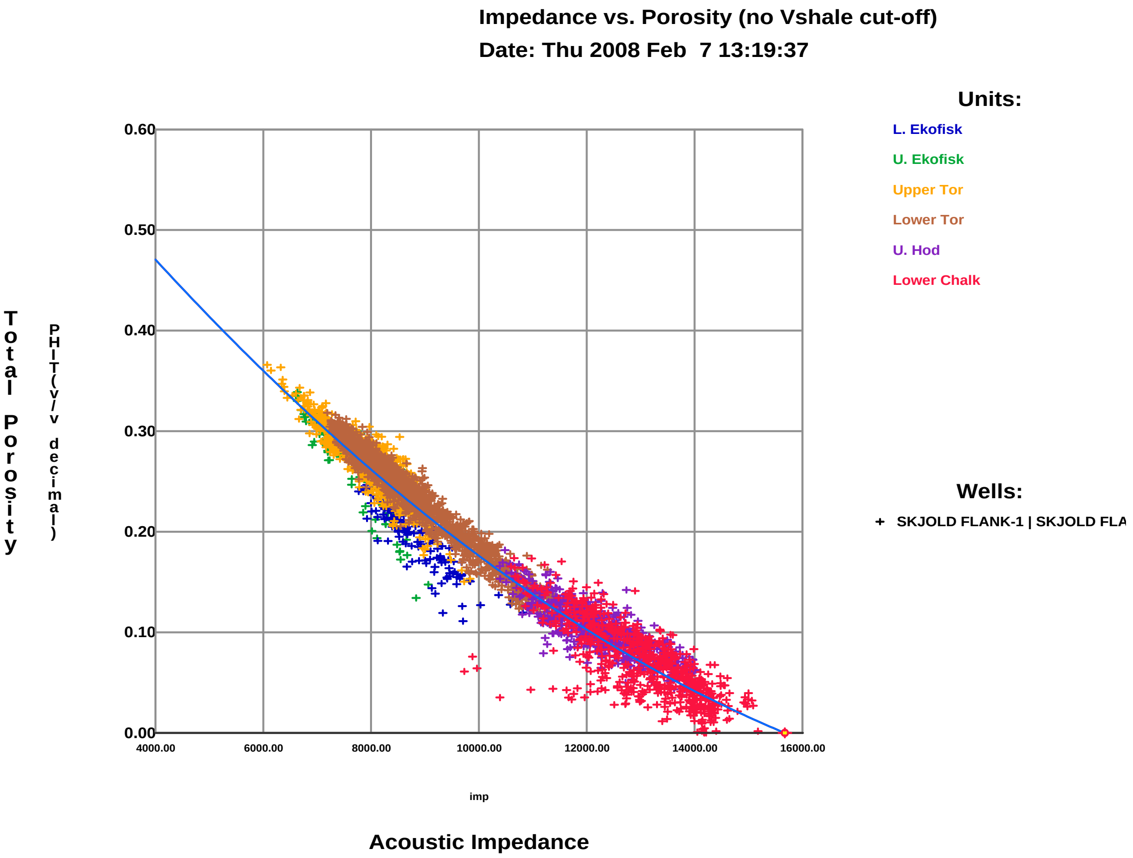


Fig. 10: Well Skjold Flank-1, AI versus porosity, split into lithostagraphic unts

Clean chalk – N/NW part of DCG

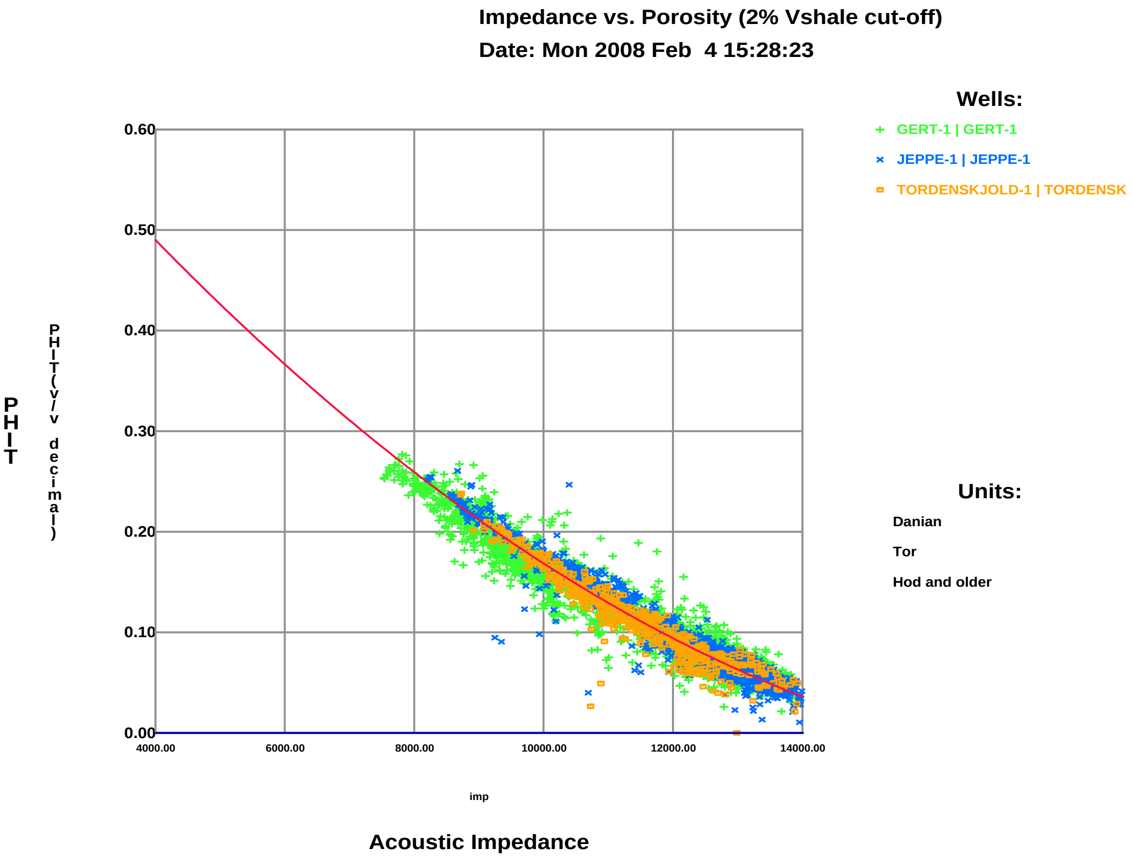


Fig. 11: Acoustic impedance versus porosity for 3 wells located towards N and NW in the Danish Central Graben. Only clean chalk is considered (2% Vshale cut -off applied).

Shale effect on AI – N/NW part of DCG

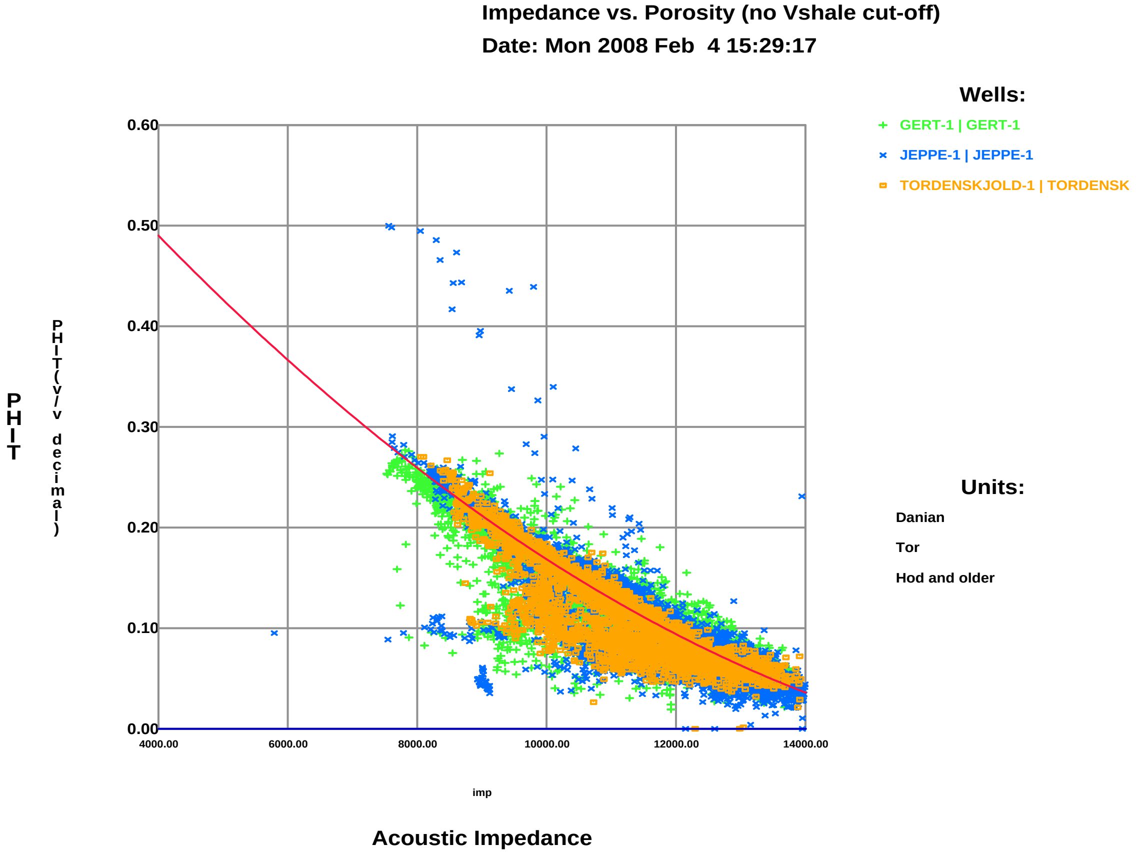


Fig. 12: Acoustic impedance versus porosity for 3 wells located towards N and NW in the Danish Central Graben. Illustration of shale effect, no Vshale cut -off applied.

P velocity for Karl-1
Clean chalk

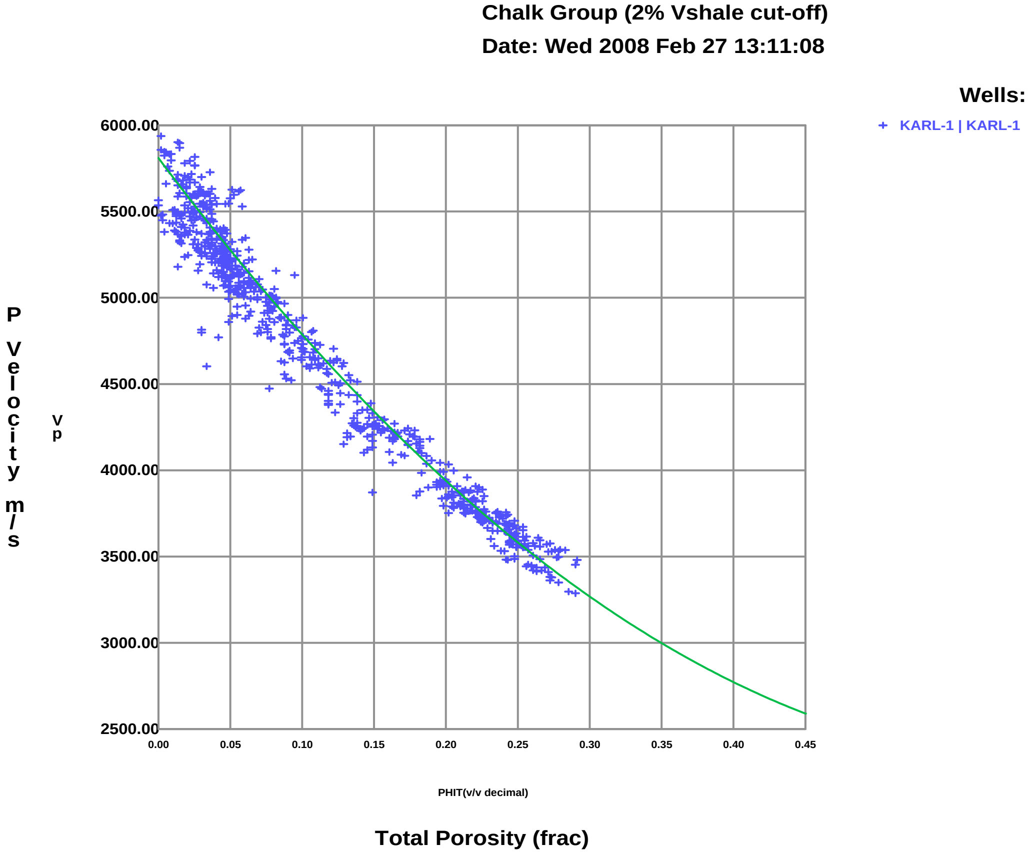


Fig. 13: Well Karl-1. Chalk Group velocity (Vp) versus porosity for clean chalk (2% Vshale cut-off). Regression line as in Figure 3

P velocity for Karl-1
No Vshale cut-off

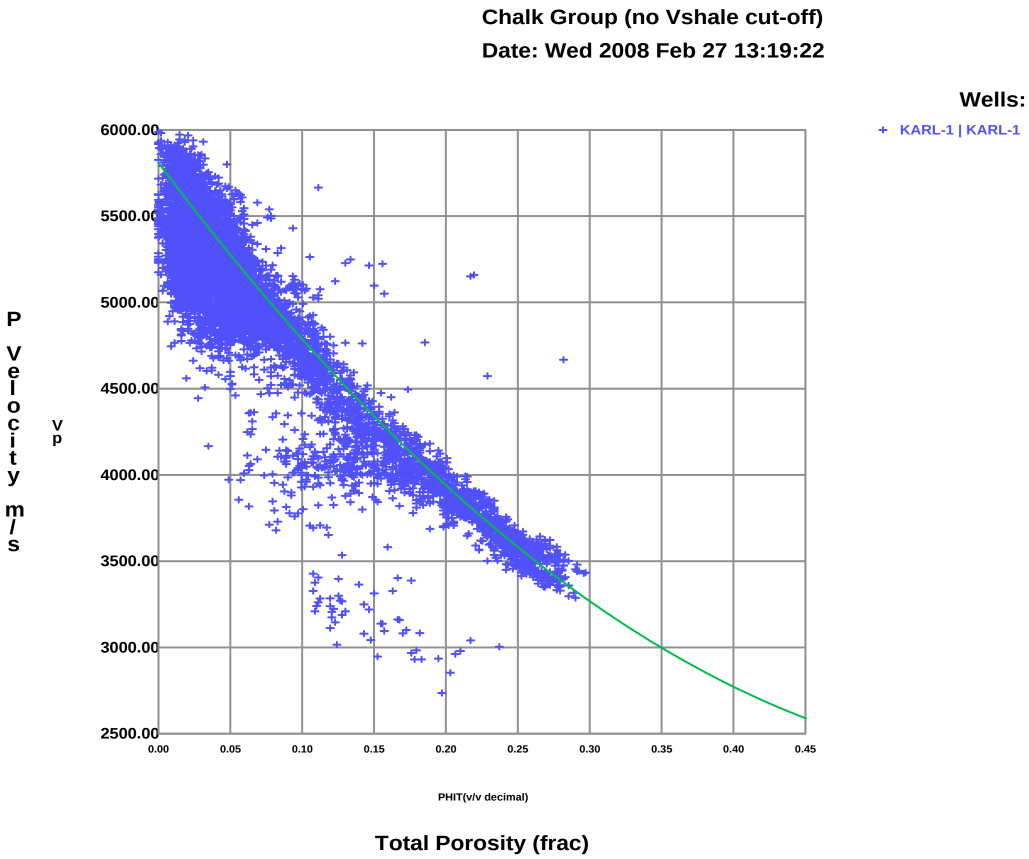
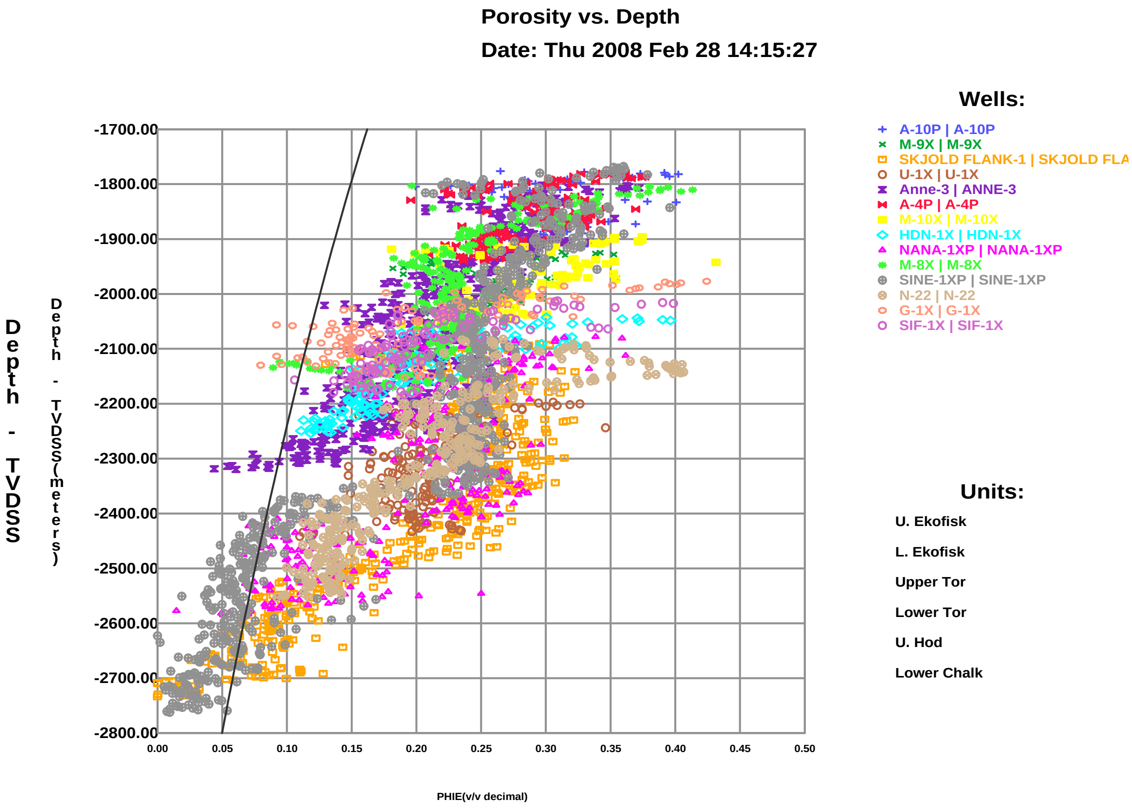


Fig. 14: Well Karl-1. Chalk Group velocity (Vp) versus porosity for the entire Chalk Group (no Vshale cut-off applied). Regression line as in Figure 3

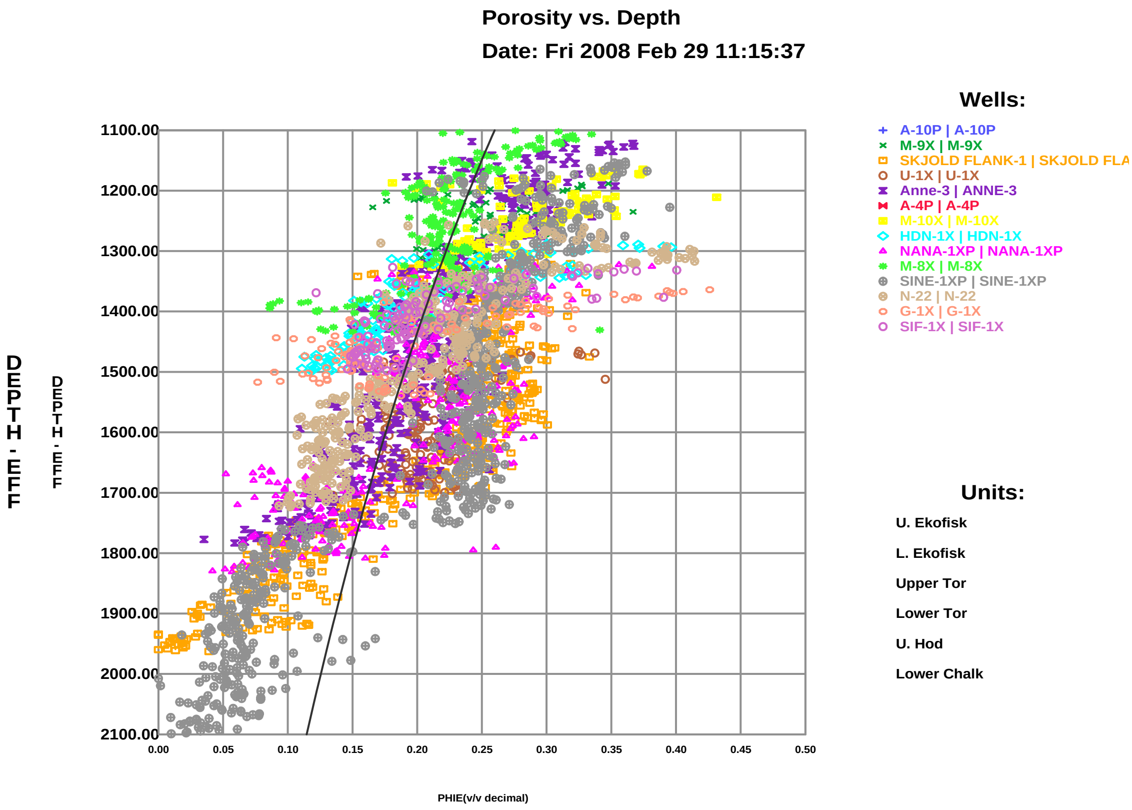
Porosity – Depth trends
Porosity versus vertical depth – Chalk Group



Effective prosity

Fig. 15: Effective porosity versus vertical depth for the entire Chalk Group – 14 selected wells from the southern part of the Danish Central Graben
Black solid line: Scholle curve

Porosity versus effective depth – Chalk Group



Effective porosity

Fig. 16: Effective porosity versus effective depth for the entire Chalk Group – 14 selected wells in the southern part of the Danish Central Graben. Black solid line: Scholle curve

Porosity versus vertical depth

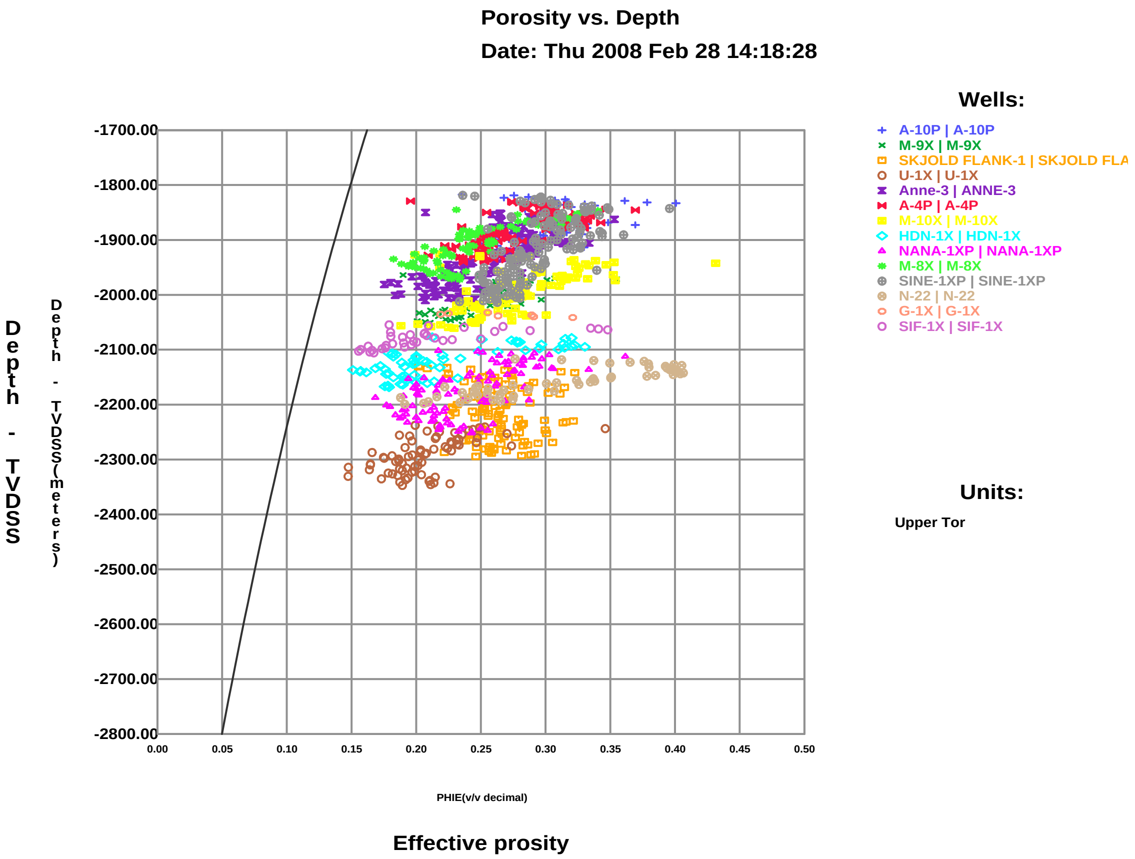


Fig. 17: Effective porosity versus vertical depth for the Upper Tor Formation; 14 wells. Black solid line: Scholle curve

Porosity versus effective depth

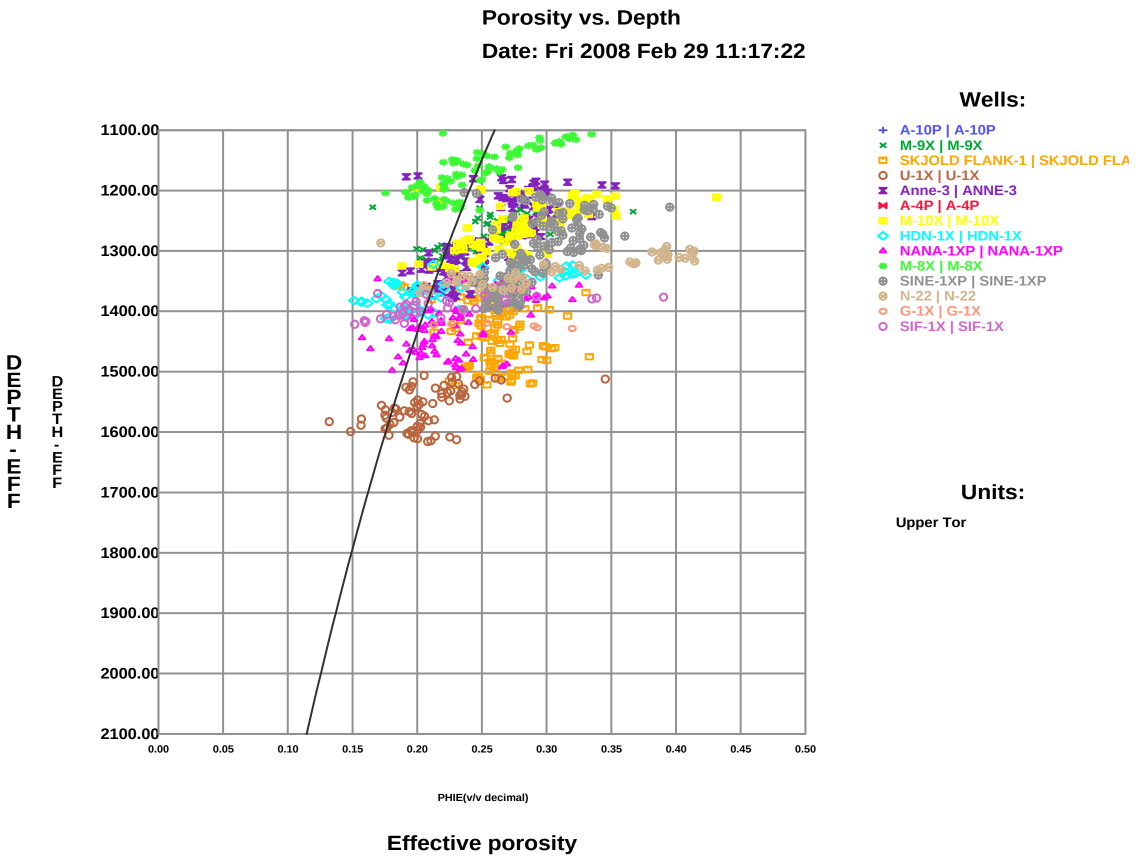


Fig. 18: Effective porosity versus effective depth for the Upper Tor Formation, 14 wells. Black solid line: Scholle curve

Porosity versus vertical depth

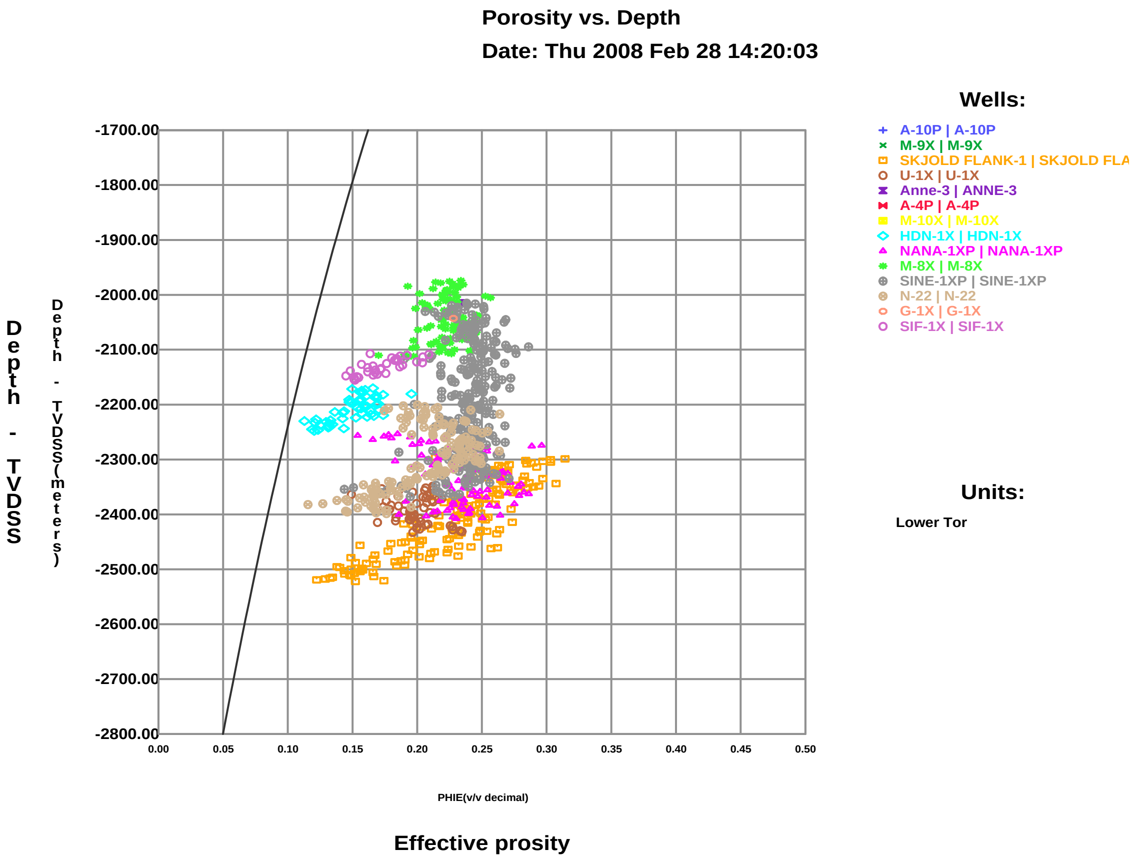


Fig. 19: Effective porosity versus vertical depth for the Lower Tor Formation; 14 wells. Black solid line: Scholle curve

Porosity versus effective depth

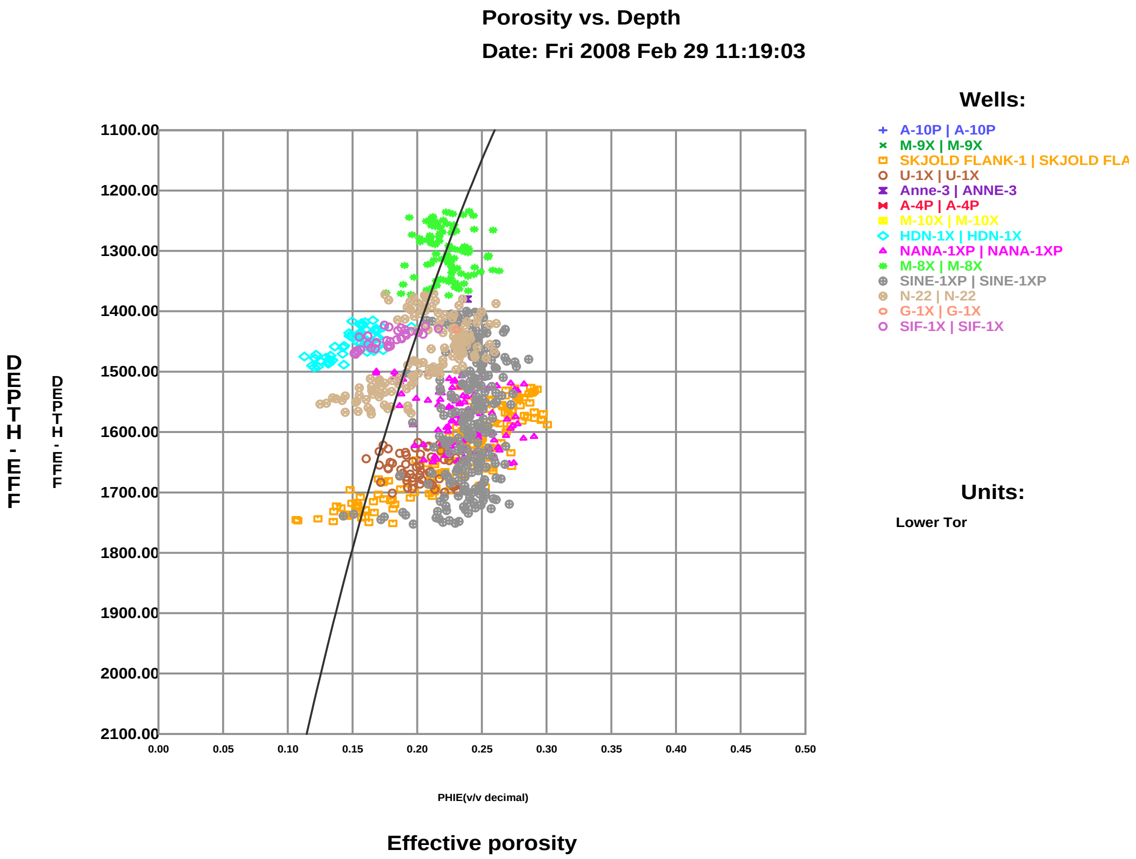


Fig. 20: Effective porosity versus effective depth for the Lower Tor Formation, 14 wells. Black solid line: Scholle curve

Porosity versus vertical depth

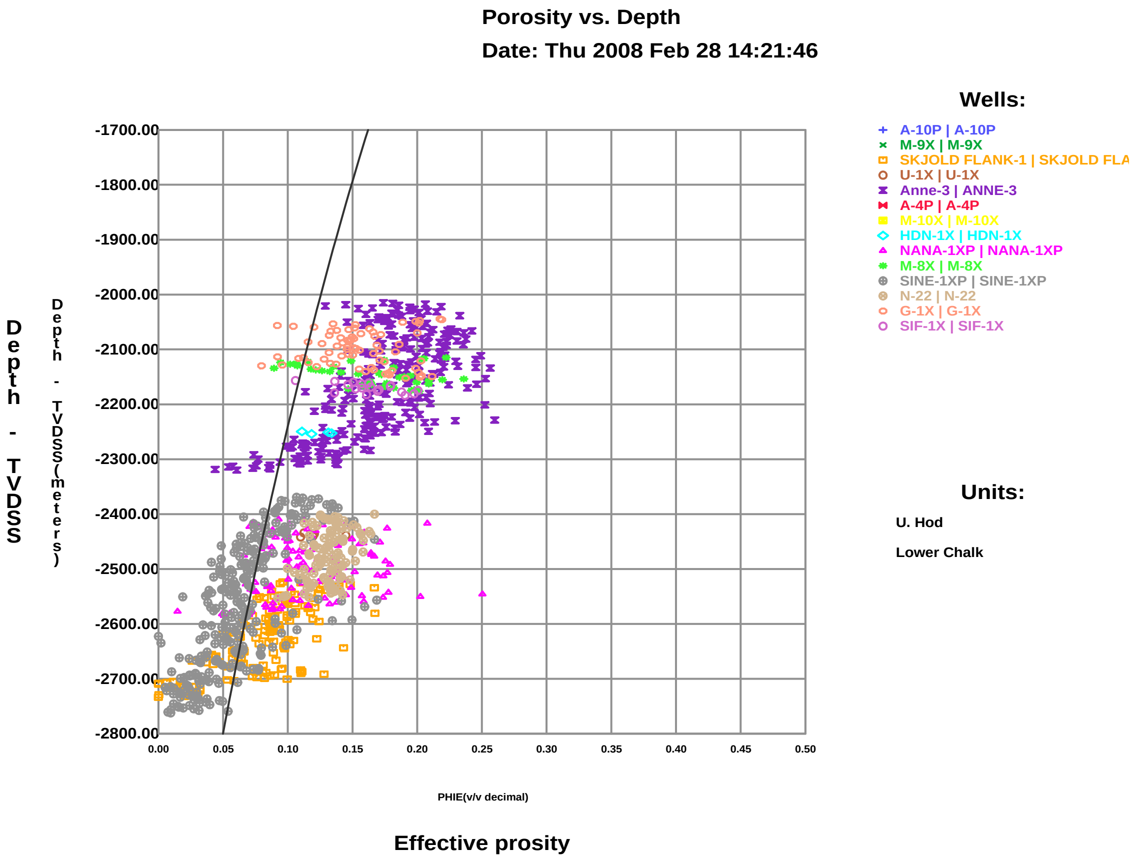


Fig. 21: Effective porosity versus vertical depth for the Upper Hod and older chalk units; 14 wells. Black solid line: Scholle curve

Porosity versus effective depth

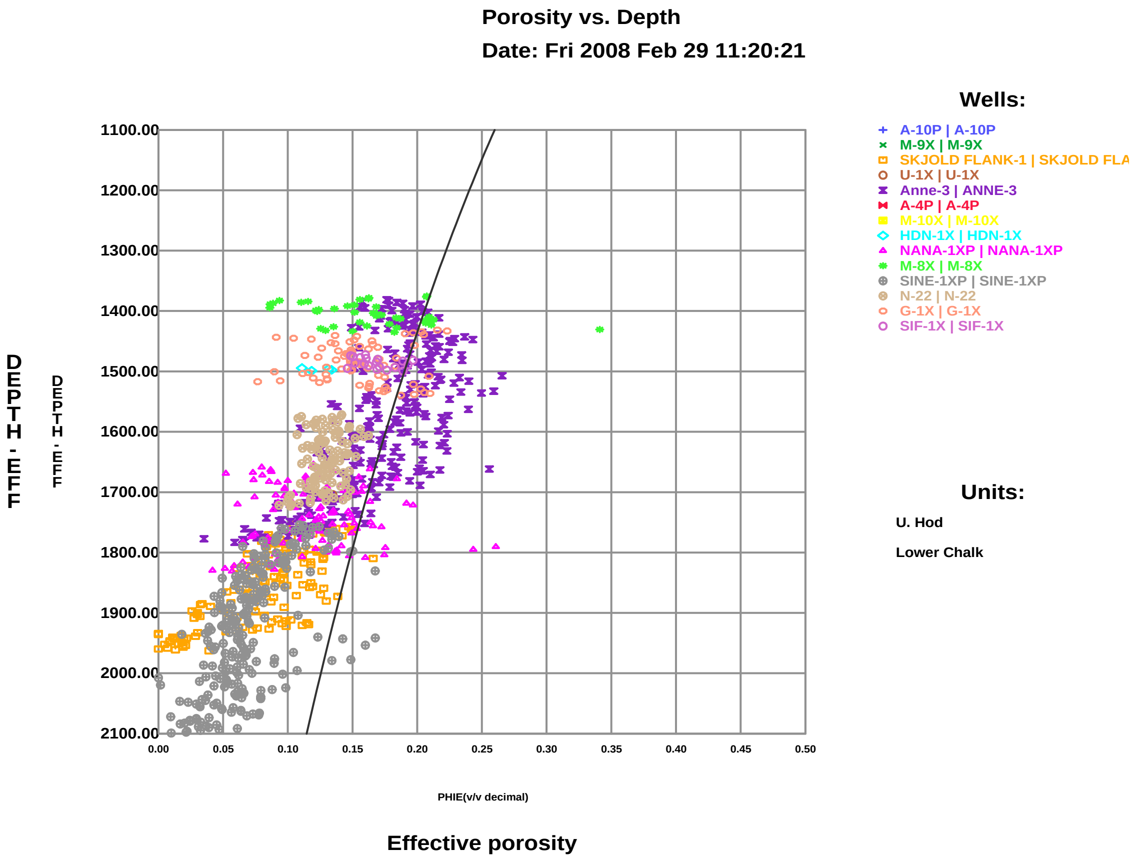


Fig. 22: Effective porosity versus effective depth for Upper Hod and older chalk units, 14 wells. Black solid line: Scholle curve